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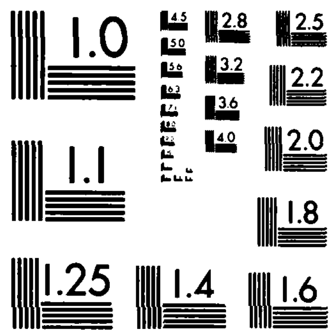

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INTERACTION AMONG INHOMOGENEITIES AND INCLUSIONS

FINAL REPORT

T. MURA

January 22, 1985

U.S. ARMY RESEARCH OFFICE

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NORTHWESTERN UNIVERSITY
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Inhomogeneities, Inclusions, Soundless Demolition, Composite Materials, Fatigue Crack Initiation, Half-Space Problems, Sliding Inclusions.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Research results performed during this research contract are summarized in the following pages.

List of Papers Published under ARO Sponsorship During This Period.

K. Tanaka and T. Mura, "Dislocation Dipole Models for Fatigue Crack Initiation", Mechanics of Fatigue, ed. T. Mura, ASME, AMD Vol. 47, pp. 111-131 (1981).

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T. Mori and T. Mura, "An Inclusion Model for Crack Arrest in Fiber Reinforced Materials, Mechanical of Materials, 3 (1984) 193-198.

Scientific Personnel Supported by this project:

Dr. R. Furuhashi, Dr. T. Mori, Dr. J. Dundurs, G.L. Lance (MS earned), N. Ahmadi (Ph.D. earned), Dr. N. Kinoshita, Dr. K. Tanaka, Dr. Y. Hirose, Dr. E.N. Mastrojannis, M.E. Gomez (MS earned), Dr. E. Tsuchida, R. Castles (Ph.D. earned), I. Jasiuk (working for Ph.D.), D. Kouris (working for Ph.D.), Dr. R. Krizek, Dr. Y. Murakami

Statement of Problems and Summary of Results:

Soundless Demolition

When powder of calcium oxide reacts with water, it expands enormously to form calcium hydroxide. This powder can be used for a soundless and safe demolition agent. It does not cause any flyrock, noise, ground vibration, gas, duct and any other environmental pollution. When holes with diameter D are drilled in a rock in a series with distance L and they are filled with the demolition agent, the necessary and sufficient distance L for demolition of the rock is calculated as the linear function of D. The coefficient of the linearity is expressed in terms of the free expansion strain (eigenstrain), the elastic moduli of the rock and the solidified demolition agent, and the fracture stress of rock. The width of created cracks is also calculated in terms of these physical and geometrical parameters.

Mechanical Property of Composite Materials

The stress relaxation caused by diffusion round a second phase particle has been measured by internal friction in Al-Si alloys. Reproducible clear internal friction peaks were found at ~ 420 K at a frequency of ~ 1 Hz. These were unambiguously assigned to the presence of Si particles in Al. In accordance with a theory of the relaxation caused by diffusion along the matrix-particle interface, the relaxation time is proportional to the third power of the particle size. The activation energy and the pre-exponential factor of this diffusion are $\sim 0{\cdot}92$eV and $\sim 3{\cdot}9 \times 10^{-5}m^2/s$, respectively. The magnitude of the relaxation strength agrees with the theory.

Our recent work on the equivalent inclusion method in connection with composite materials is further developed to obtain the interaction between composite elements, the image stress due to free surface, convergency of series for a periodic distribution of inclusions, existence of impotent inclusions, and relaxation of inclusions. It is also discussed that the stress field for points exterior to the inclusions and inhomogeneities can easily be obtained if the solution for a void under an arbitrary load is known. The results obtained seem to be important in fracture mechanics and constitutive relations of composite materials.

A tensile crack bridged by strong and tough fibers is modeled in such a manner that it can be analyzed based on concepts from the mechanics of inclusion. Analytical expressions for the energy release rate, stress intensity factor and crack opening are derived. It is shown that the presence of the supporting fibers reduces the values of those quantities which saturate at a certain level determined by the size and spacing of the fibers.

Fatigue Crack Initiation and Propagation

A dislocation dipole model is proposed to explain consistently the following phenomena and empirical equations observed in cyclic loadings of materials.

1) Damage accumulation.
2) Ratcheting of plastic deformation in forward and backward directions.
3) Extrusions and intrusions.
4) Dislocation dipole structure of persistent slip bands
5) Coffin-Manson's law.
6) Petch's equation.
7) Crack initiation along grain boundaries.
8) The fatigue strength reductions due to inclusions and notches.
9) Neuber's and Peterson's formulae.
10) Anomalous behavior of small cracks.

The damage accumulation of cyclic loadings is assumed to be accumulation of dislocations. The fatigue crack initiates when the self energy of dislocations accumulated during n cycles of loading become a critical value. This dislocation dipole model is extended for fatigue crack initiation at inclusion interfaces or notch tips. Reduction of fatigue crack initiation life due to inclusions is predicted for the two cases when the fatigue crack initiates from a completely debonded inclusion and when the slip band crack emanates from an uncracked inlcusion. The fatigue strength of notched specimens relative to that of smooth specimens decreases with increasing the stress concentration factors, notch sizes, and notch root radii.

Fatigue crack propagation along planar slip bands under a mixed mode loading is analyzed based on the dislocation dipole model. Fatigue damage is systematically accumulated within the slip bands with increasing dislocation dipoles and the resulting strain energy density to be a critical value yields crack growth. The propagation rate is given as the crack growth distance in each step divided by the number of cycles to the formation of a new crack ahead of the old crack. The range of cyclic shear stress in a mixed mode acting on the slip plane directly controls the rate of damage accumulation, and the normal stress component provides an additional strain energy release to accelerate fatigue crack growth. The material parameters involved in the theory are the grain size, the dislocation friction stress, and the specific fracture energy. The theory is applied to Stage I fatigue crack growth observed in high-strength alloys, and it is further extended to the near-threshold growth of a long fatigue crack.

The evolution of dislocation structures during fatigue of metals is investigated in terms of the elastic strain energy of the structures. The ladders in persistent slip bands and the tangling dislocation dipoles in vein structures are simulated by inclusions with uniform eigenstrain ϵ^{*}_{11}. The theory explains why persistent slip bands have ladders.

Crack nucleation mechanism of hydrogen assisted cracking at notch tips in aqueous solution is proposed by a model of dislocation pileups and hydrogen atom diffusion along the pileup line. The theory predicts the relation

between the detached crack distance and notch radii and the crack nucleation time as a function of the apparent stress intensity factor. The theory is extended to the case of cyclic loading, where a model of dislocation dipoles is used. The theory agrees with experimental data for 4340 steel.

Half-Space Problems

The half-space problem is a special case of two inhomogeneities, where one inhomogeneity is an infinite void.

Stress distributions are evaluated for a semi-infinite elastic body having a spheroidal inhomogeneity under an all-around tension (axi-symmetric uniform tension) at infinity. Boussinesq's potential functions are used for the analysis. A special technique is employed for the traction-free condition on the free surface, where the ordinary Legendre functions are expressed in terms of the Bessel functions in cylindrical coordinates. A closed form expression for the stress concentration factor is found for a special case of a needle-like inhomogeneity.

As a related problem, a numerical method is proposed for design of contact profile under prescribed pressure distribution.

Sliding Inclusions

We have found an unexpected result for a sliding inclusion. It is found that when an ellipsoidal inclusion undergoes a uniform shear eigenstrain (non-elastic shear deformation) coinciding with the axes of the inclusion and the inclusion is free to slip along the interface, the stress field vanishes everywhere in the inclusion and the matrix. This indicates that many results obtained from Eshelby's solution for the perfectly bonded inclusion must be substantially modified when inclusions are allowed to slip along interfaces.

When an inclusion is perfectly bonded, the eigenstress (residual stress) caused by the uniform shear eigenstrain is non-zero and evaluated by Eshelby's calculation. This stress is a back stress for inhomogeneous plastic deformations which plays an important role in the workhardening theory and in the self-consistent theory of composite materials. If the inclusion, however, is free to slip, no back stress is accumulated by any local shear plastic deformation according to the present result. No resistance for shear deformation is expected. This may be a characterisitc of deformation seen in superflasticity alloys and granular materials.

If the sliding inclusion is subjected to a non-shear eigenstrain, the stress configuration inside the inclusion is more complicated. It also substantially deviates from the result for a perfectly bonded inclusion of Eshelby. The stress state is not uniform and varies with coordinates in a form of infinite series of the coordinates. We have performed numerical examples of a prolate or an oblate inclusion. In calculation, the effect of free surface in a half space is also included.

Micromechanics of Defects in Solids

The principal investigator has published a book "Micromechanics of defects in solids" Martinus & Nijhoff (1982). As acknowledged in the preface of book, most of the contents of book are based upon the results of research sponsored by U.S. Army Office. The book has received extremely good book reviews in several professional journals in the fields of mechanics and materials science. A few samples are attached.

Micromechanics of Defects in Solids. By T. Mura. Martinus Nijhoff, The Hague, 1982. pp. x–494. Price $98.00.

REVIEWED BY D. M. BARNETT[6]

Much of what might be termed advances in the mathematical treatment of defects (inclusions, inhomogeneities, dislocations, and cracks) in solids tends to be scattered throughout the journal literature; as a result, the researcher intent on entering this field faces the rather formidable task of deciding on the best way in which to begin learning about the theory of defects. Prior to the appearance of Professor Mura's monograph, *the* single outstanding text available to such a researcher was *Theory of Dislocations* by J. P. Hirth and J. Lothe, now available in its second edition. The Hirth and Lothe book is, in my opinion, a beautiful exposition of great lasting value. Nonetheless, I have long had the feeling that it is more easily digested by one trained in solid state physics or materials science than by one whose primary bent is solid mechanics; in addition, Hirth and Lothe devote very little space to J. D. Eshelby's famous "transformation strain" problem, whose solution and attendent results should be in the "bag of tricks" carried by every Ph.D. materials scientist. Professor Mura's book more than adequately fills both gaps. Over one-third of the book is devoted to the treatment of inclusions and inhomogeneities in isotropic and anisotropic linear elastic solids, and the development of the subject matter should please readers familiar with either solid mechanics or applied mathematics.

The first chapter introduces the notion of eigenstrains and emphasizes in a self-contained way the use of elastic Green's functions to represent the solution to eigenstrain problems. The next three chapters provide a most complete survey of inclusion and inhomogeneity problems and contain a wealth of formulas which should prove most useful to those requiring solutions to this class of problems. Cracks and dislocations in elastic solids receive a reasonably complete treatment in chapters 5 and 6. The final chapter emphasizes the use of techniques and solutions introduced previously to model phenomena of importance to mechanical metallurgists, including work-hardening of dispersion strengthened alloys, stress relaxation via diffusion, and polycrystal plasticity.

In summary, Professor Mura's book may be heartily recommended to those interested in either applying or learning to apply the methods of continuum mechanics to treat defects in the solid state. This monograph could serve as the perfect text for a second-level graduate course with the same title as that of the book.

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June 1983, Vol. 50, page 477

Journal of Metals, November 1983

Micromechanics of Defects in Solids.
By Toshio Mura.

1982, Martinus Nijhoff Publishers, P.O. Box 566, 2501 CN, The Hague, The Netherlands. Hardbound, 494 pages US $98.00.

Micromechanics of Defects in Solids has developed out of a course that the author has taught for several years at Northwestern University. The book covers a comprehensive mechanics treatment of the microstructural features of a material that govern the deformation behavior of the material. Examples of such features include inclusions, dislocations, discontinuities and cracks, phase transformations, and precipitates. A broad spectrum of mechanical behavior of materials has been analyzed based on the continuum theory of elasticity and the "eigenstrain method." Such behaviors include fracture, fatigue, and plasticity.

The book is divided into seven chapters with the first chapter devoted to the development of the general theory of eigenstrains. Each of the subsequent chapters deals with specific microstructural features. Chapters 2 and 3 deal with isotropic and anisotropic inclusions, respectively. Chapter 4 deals with ellipsoidal inhomogeneities while Chapter 5 deals with cracks. Dislocations and their stress and displacement fields are discussed in Chapter 6. Finally, Chapter 7 deals with a variety of subjects, such as work hardenings of dispersion hardened alloys, plastic behavior of polycrystalline metals and composites, and interaction between dislocations and inclusions.

The book explains the necessary physics and mathematics behind the various developments. It could not only be employed to teach an advanced level graduate course, but would also be very useful to researchers in the field of micromechanics of deformation of solids.

Ravi Rungta
Battelle

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